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ACTIVE PHASED ARRAY RADAR ANALYSIS

by

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September, 1996

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ACTIVE PHASED ARRAY RADAR ANALYSIS

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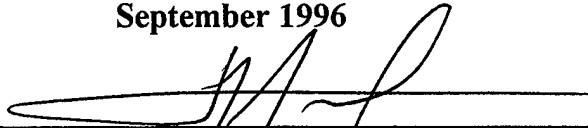
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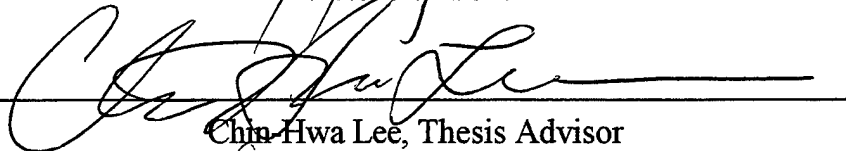
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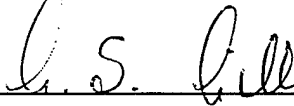


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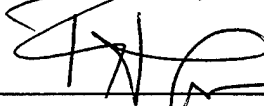
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ABSTRACT

A phased array antenna can electronically steer the direction of the antenna beam almost instantaneously. In an Active Phased Array Radar (APAR), this capability is used to allow the system to multiplex its time between many different functions; the primary functions are search and target tracking. Potentially, the APAR can be designed based on the task it is performing, such that any savings in radar time in meeting the requirement of one task allow that time to be devoted beneficially to other tasks. The primary goal of this research is to investigate the performance assessment and improve the techniques for control of an Active Phased Array Radar performing the tracking function. In order to reliably and efficiently track targets, a MS. Excel 5.0 Spread Sheet program is implemented so that tracking range must be rapidly changed. With this program we can explore the many degrees of freedom that future APAR's will bring, such as adaptable update rate, antenna beamwidth, transmitted power, frequency, etc.

TABLE OF CONTENTS

I. INTRODUCTION.....	1
A. OVERVIEW	1
B. PHASED ARRAY ANTENNAS	2
II. ACTIVE PHASED ARRAYS.....	5
A. INTRODUCTION.....	5
B. BASIC CONFIGURATION ..	11
C. KEY COMPONENTS	14
1. Transmitter-Receiver Modules	14
a. The device	18
b. Power Amplifier	19
c. Phase Shifter	20
2. Feed And Control Network	22
a. Control Network	24
b. Power Supply requirement aspects	24
3. Antenna and T-R Module Coupling	25
D. MANUFACTURABILITY AND COST	28
III. RADAR PARAMETERS AND DESIGN	31
A. RADAR.....	31
1. The Radar Equation	32

2. The Searching Function	36
3. The Tracking Function	37
4. Radar Functions Dependencies	38
5. Angular Accuracy as the Key	39
6. Maximum Radar Range Performance and the Angular Accuracy Relationship in the Active Phased Array Radar Tracking Function	41
IV. SYSTEM PERFORMANCE ASSESSMENT	43
A. ESTIMATED RADAR PARAMETERS	43
B. DETERMINED RADAR PARAMETERS	44
C. MAXIMUM RANGE PERFORMANCE	49
V. CONCLUSIONS	51
APPENDIX	55
LIST OF REFERENCES	59
INITIAL DISTRIBUTION LIST	65

LIST OF FIGURES

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Figure 1.	Block diagram of Active Phased Array	12
Figure 2.	T-R module block diagram	17
Figure 3.	Patch array layout	26
Figure 4.	Two-layer feed system	27
Figure 5.	Radar example	32
Figure 6.	Power received by radar due to target located at range R with RCS σ	34

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I. INTRODUCTION

A. OVERVIEW

Since the beginning of radar systems around 60 years ago, there have been continued efforts to improve its performance in its many applications.

The proliferation of advanced technologies threats, such as low-radar-cross section targets (enemy ships, missiles, etc.), their increased speed and altitude, etc., have impacted the US Department of Defense. Consequently the US Federal Government have to spend more funds in Research and Development programs such as Monolithic Microwave Millimeter Integrated Circuits (MMIC), very High Speed Integrated Circuits (VHSIC), and Active Aperture Phased Array Radar (APAR) to maintain superiority in its defense capabilities and military power (Brukiewa, 1992).

In this work first, the main characteristics and the parameters of the Active Phased Array Radar will be investigated. Later on, the effect of these parameters on the Radar Range Equation for the tracking function will be assessed.

The tracking accuracy requirements are usually given by the users in terms of those which support reactions to the presence of a target in the radar environment. Also, an inherent minimum tracking capability is required within the radar, which is associated with the dynamics of the target. The main characteristics of the potential target (shape, dynamics, etc.) is an important part of the radar specification. Track rates should not be specified unless they are of specific, identifiable importance to the user.

The APAR, with its inherent flexibility, can also provide a widely varying tracking function. Track, like search, should be specified over a range of values for a variety of

situations. Different kind of priorities have be assigned to different classes of targets or targets in a selected direction, while maintaining track on all targets. The required data rate for targets of different priorities may vary too. Therefore, those specifications may stipulate how the track performance is allowed to degrade with different situations. Because the target arrival rate can have a significant effect on the design of an APAR, at least those limits should be stipulated.

The variants of time and space must be addressed in a more significant manner for an APAR than for the suite of radars that otherwise would be used (Billeter, 1989). While many different types of radars are used, the operating parameters of each can be optimized for its environment and its task.

B. PHASED ARRAY ANTENNAS

The present study is motivated by the renewed interest in the field of phased array radars and particularly in Active Phased Array Radars (APAR) as a result of advances in microwave technology, digital signal processing and integrated circuits. Phased arrays radars are distinguished from other radars by phased array antennas which are capable of steering the beam electronically in space. This provides a greater flexibility, makes the system much more versatile by being able to carry out better energy management in the volume of space, and optimizes the search and track functions. Phased arrays thus represent the best sensor configuration for military radar applications nowadays.

Phased arrays belong to that class of array antennas which can provide beam agility by changing the phase progressively between successive radiating elements (Galati, 1993).

But the performance of phased array antennas is limited by the characteristics of array antennas and the beam scanning effects. Despite the fact that the work on phased array technology was initiated more than three decades ago, the development of the array technology was slow primarily because of the high cost of the components. The cost per active array element is still not low, but in the last fifteen years the increasing demands for radar systems with better performance have resulted in the incorporation of features like beam agility, multi-target tracking, antenna pattern control, electronic counter-measures and multimoding (Rudge, 1986).

The study of phased arrays antennas in the analytical and experimental field, including the behavior of a variety of radiating elements in finite, as well as in large array environments, contributed to the solutions for large array systems. Understanding of boundary effects, some phenomenon like arrays blindness plus advances in signal processing have all led to a better understanding of these systems.

There have been significant improvements also in phase shifters, feed networks, microstrip, stripline radiators, and broadbanding of arrays. The final goal of making the two dimensional phased array system cost-effective will be achieved by means of printed circuit board technology, utilizing printed circuit antenna arrays (PCAAs) based on microstrip patch or printed dipole (Knittel, 1979). These devices will be fabricated as sub-arrays containing a number of them along with associated phase shifting and driver electronics so that techniques used in digital integrated circuit production can be fruitfully employed. Computer aided design of these arrays as well as computer aided manufacturing will become mandatory.

Phased array radars can use either passive or active apertures. In the passive-aperture approach, the array modules must be fed from a divider network which distributes the available power with the appropriate amplitude taper among the array elements. In the active-aperture approach, each array element contains a transmitter and a low-noise receiver. The transmitter is usually a solid-state amplifier device which tends to favor frequencies at L band or below where reasonable efficiencies can be achieved. An advantage of this approach is that large radiated powers can be generated by the spatially coherent addition of a large number of low-power devices. Low power monolithic transceiver modules (TR modules) are being developed for this application (Schleher, 1994).

II. ACTIVE PHASED ARRAYS

This chapter describes the Active Phased Arrays and a configuration for a basic system. Main characteristics of its components and the desired properties are addressed.

A. INTRODUCTION

Active aperture phased array has become important in the last five years mainly because it is the technology which holds out the promise of realizing affordable electronic scanning radar sensors. The search for an economical method to incorporate electronic scanning has been initiated in the late 1970s because of the low rate of introduction of phased array radars even though the technology was more than one decade old (Yaw, 1981). It was accepted that the cost of phased array antennas cannot be lowered to a level where they can be as widely used as the mechanically scanning reflector antennas. It should be possible to improve the design and production of phased arrays to reduce costs.

It is a fact that in most searching and tracking radar sensors such as airborne, ground based or shipborne, a minimum amount of electronic control has already been used for beam forming, shaping and scanning by employing planar phased array antennas (Walsh, 1988). Even with such limited application, substantial progress has been made in the understanding of mutual coupling effects and in compensatory microwave circuit design, phase shifting networks and integrated radiators (Galati, 1993). Such phased array antennas are currently being assembled by integrating individual radiating elements, phase shifting and matching networks and further testing on a unit-by-unit basis (Elliot, 1981).

This has proved to be expensive, and alternative approaches which make full use of production techniques were perfected in large volume production of integrated circuits. The active aperture array concept, in which the individual radiating element is easily combined within a module which transmits RF power of adequate level in phase synchronism with other such modules in the array and receives RF energy in the receive mode, thus appears to be the most promising solution (Amitay, 1972).

The idea of active aperture phased array dates back to 1964 when the AN/FPS-85 development was initiated for a radar operating in the UHF band with 4660 active elements in the phased array (Brookner, 1979). The active array development appears to have been motivated by the need for realization of a large power-aperture product, since each of these active elements generated 10 kW of peak RF power. At the same time, some work on solid state active arrays was started for developing MERA (Molecular Electronics for Radar Application), an experimental X-band system (Billam, 1985). The primary objective was to improve the conventional approach of interconnecting many RF functions so that more microwave circuit functions can be accommodated in a limited space. The microwave integrated circuit packages also provided other advantages such as higher reliability and increased performance due to reduced interconnections. MERA was completed in 1969 and was followed by RASSR (Reliable Advanced Solid State Radar) to demonstrate that a practical active aperture phased array radar system can be built. It brings out that reliability improvement due to solid state devices available in such systems (Hartwell, 1977). However, the technology of RASSR was not followed through in production for other radars built after 1975, because a direct power source and a low noise amplifier at microwave frequencies were not available in the desired configuration.

The advent of the field effect transistor effectively closed this gap so that it would be possible to have solid state T-R (transmitter-receiver) modules with low noise figures in the receive path and higher output powers for transmissions, manufactured in sufficiently large numbers (Edwards, 1982). Since then, there have been significant advances in the technology of active and passive components used in T-R modules. The emphasis is reduction of size and volume for both types and better efficiency in power devices. Currently opinion exists that, for radars operating in the lower microwave frequencies (up to 6 GHz), hybrid T-R modules may be a better answer firstly because they are less expensive and secondly because they can deliver power levels beyond the reach of a single chip (Priolo, 1990). This picture is, however, changing towards higher functional integration, and currently the linear gallium arsenide integrated circuit, known as the monolithic microwave integrated circuit or MMIC, will replace other circuit configurations because it combines the field effect transistor and the microwave integrated circuit technologies in a single chip (Zaghloul, 1989). As a result of this, the parasitics are reduced and the reliability is improved, which lead to enhanced performance. The MMIC also has potentially reduced cost, and reduced manufacturing time scales for high volumes. However, the MMICs place an additional weight on the microwave designer in that he must commit to a final circuit very early because the small size chip prevents tuning or changing circuits during testing to peak the performance. Further, for realizing the benefit of cost reduction, the antenna configuration has to be compatible with the transmission line configuration of the T-R module to which the radiator will be joined. Since microstrip lines are used extensively in the T-R module for connecting the variable network elements, the only compatible configuration would be the PCA or the printed circuit antenna. PCA

would therefore replace the waveguide excited slot or aperture or the coaxial transmission-line compatible rounded dipole as the antenna element in active aperture phased arrays (Das, 1992). In the last two decades considerable information and understanding of the behavior of these elements in the finite as well as in the infinite array environment had been gathered by experiment and confirmed by theoretical studies. These will be used in resolving problems likely to arise in printed circuit array antennas (Tsai, 1983).

In an active aperture array, therefore, the RF power sources as well as the RF portion of the receiver chain are distributed across the array. Phased array radars in the future can be built by going to active aperture so that thousands of T-R modules needed in the sensor can be economically manufactured by techniques of lithography. Printed circuit antenna arrays (PCAA), MMIC techniques for T-R modules, VLSI chips and fiber optic techniques are expected to play a large part in the development of future radar systems (Bar-lev 1984). Active aperture radar is therefore *"a favoured design that provides greater benefits with the forthcoming increases in signal and computer control capabilities. The active array offers advantages in areas of power management, beam steering, target detection and system performance. Active arrays may also give advantages in weight and volume"* (Morchin, 1990). Hence there should be no doubt about the necessity of these advances in radar systems of the future, especially as the present efforts to reduce the cost of fabrication bears fruit in the next few years.

It is interesting to note that similar conclusions can be arrived at if one views the progress that has taken place in technology. Already the active aperture technology has matured to allow its application in radar systems production in the 1990s. The evolution of

the monolithic microwave integrated circuit (MMIC) technology for active aperture in AESA (Active Electronically Scanning Array) application has been the final step in system efficiency and cost reduction, making it the preferred technology for all future multimode radar developments (Lockerd, 1990). The main arguments in support of this conclusion are as follows.

Over the years, the power output of the T-R modules has gone up and the efficiencies have also shown a significant upward inclination. For example in X-band, solid state devices have progressed from 1 W peak power and junction efficiency of 15% to approximately 10 W peak and junction efficiencies of 40% in less than two decades (Vorhaus, 1989).

There has been considerable progress in the last 15 years in MMIC realization from a single function module to multifunction modules containing power amplifier, low noise amplifier, phase shifting network, limiters, switches etc. The progress, especially in the last five years, has been very significant as evidenced from a comparison of typical MMIC multifunction modules of 1986 and those of today. The present module has a lower component count (59 versus 348), fewer subassemblies (2 versus 5) and fewer interconnections (200 versus 561) (Naster, 1987).

There is a major program of development designed to ensure not only the millimeter and microwave monolithic circuits but also the processes by which such circuit can be designed rapidly, repeatedly and produced at lower costs (Pavio, 1989). In addition, there are other programs for optimizing the performance, reliability and cost envelopes of the components used in these modules.

A key component in implementing such arrays with minimum performance degradation is the power supply for T-R modules. The effort is to develop compact, highly reliable power supplies to give low voltage, high current low noise power with densities of 50 W/in^3 as against the present capability of 10 W/in^3 (Zaghloul, 1989).

There are two important radar system developments, one for airborne and the other for ground based applications, that have been initiated for demonstrating the key performance factors, cost and reliability-availability-maintainability (RAM) features of active phased array radars (Sparks, 1989). The first one is the Ultra Reliable Radar (URR) program using an 813 mm diameter solid state phased array (SSPA) containing 1980 T-R modules. This radar will generate different beam shapes such as pencil and wide pencil, cosecant squared, wide fan beam, thinned pencil and dual beam modes by controlling the state of each T-R module. The second one is an Active Phased Aperture Radar (APAR) employing MMIC, VHSIC, optical and bistatic technologies to meet the requirements of the late 1990s. APAR has significantly expanded multifunction capabilities and is expected to achieve 50% savings in acquisition cost, a 10:1 saving in life cycle cost, a 7:1 increase in availability, a 50-60% saving in prime power and a 50% reduction in weight and volume (Galanti, 1993). This radar will have 6000 T-R modules and can be used both as a rotating or as a fixed array operating in conventional, monostatic and bistatic modes. A 1000 module APAR is planned to verify many of the key performance, cost and RAM features.

B. BASIC CONFIGURATION

The active aperture concept of RF power sources being distributed across the array eliminates the need for a feed network for distributing a large amount of RF power from a distant single high power source to the antenna aperture. On the other hand, because of the space combining aspect of RF power in these systems, the feed network deals with relatively low level signal distribution to and from the aperture. Thus each T-R module which is placed in the immediate vicinity of the radiating element of the active array will need microwave, bias, IF and digital lines to provide and process the data (Mailloux, 1982). A basic configuration of an active aperture array is shown in Figure 1.

For the consideration of clarity, three separated networks for feed and control are shown and are away from the active array. The RF distribution in this case generates the necessary microwave signals and transmits through the distribution network these signals to the power amplifiers in the transmit path of the T-R module. The phase and frequency synchronization among the modules is realized to provide the effective radiated power (EP) at the target. The microwave distribution network also provides the local oscillator (LO) signals necessary for converting the signals received through the receive channel of the T-R module into IF signals for combining, mixing and signal processing. It is also possible to conceive the combining of the received signal at the video RF level because the active aperture phased array lends itself easily to digital beam forming owing to the distributed nature of the transmit and receive channels (Billeter, 1989). More than any other configuration, the active aperture system provides great scope for control of

transmit waveform, radiation characteristics of the antenna, signal processing and target management.

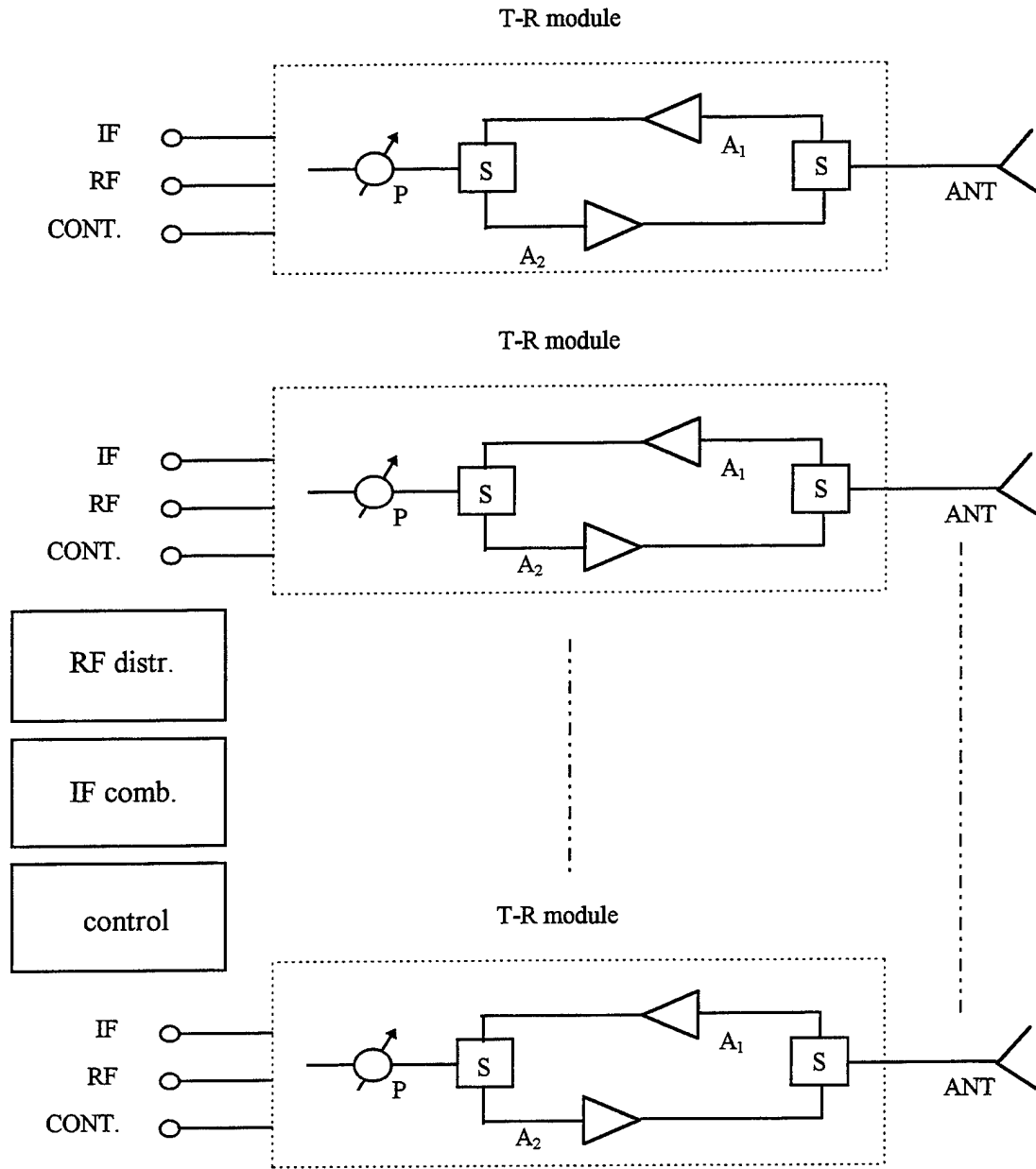


Figure 1. Block diagram of Active Phased Array

A₁ = LNA
A₂ = PA
S = switch
P = phasor

In the transmit mode of operation, the use of MMIC power amplifiers with each T-R module eliminates all the safety mechanisms that need to be built into radar transmitters for safety of operating personnel. Secondly, the distributed nature of the RF sources across the array provides graceful degradation and thus removes additional constraints that are imposed today on reliable operation of dual or standby transmitters (Chilton, 1987). Since low level RF signals are transmitted to each of the T-R modules, it is possible to incorporate with greater ease the desired digital modulation for the transmitted waveforms. Computer control of the transmitter waveform can be carried out without the attendant problems faced in high power transmitters. Further, the advantage of the distributed nature of the RF sources is in controlling the illumination function across the array. In the transmit mode, wide pencil, pencil and shaped beams can be generated on command from a common processor to alter the amplitude of the output signal either by gain control or by attenuator and the phase of the signal through the microwave digital phase shifter (Sliva, 1988). In the receive mode, since flexibility exists in the system to carry out combining the received signal through the array at the video level, it is possible to have a radiation pattern different from the transmit pattern and even to have multiple beams without loss of gain in the system (Galanti, 1993).

C. KEY COMPONENTS

Some of the important components of the Active Phased Array Radars are:

1. Transmitter-Receiver Modules

The possibility of using solid state devices in radar transmitters was initiated in the 1960s because of the obvious advantages of higher reliability, graceful degradation, on-line replacement, low voltage operation, elimination of modulators etc. (Billiam 1985). The use of low voltage power supplies also results in substantial improvement in the transmitter stability because of lower modulation sidebands. Enhanced values for the MTI improvement factor come about mainly as a result of better control on the wavelet in the power supplies which would be below 50 V. Solid state transmitters with capability of 70 dB improvement factor have been fabricated without much effort (Edwards, 1982). This approach proved that distributing RF power sources across the array to feed a group of radiating elements and providing a return path for the received signals can be engineered in field systems with higher reliability. The use of T-R modules behind the radiating aperture thus became a viable architecture. However, the technology of fabrication in this case was microwave integrated circuits (MIC) or hybrid MIC which is not compatible with array lattice configurations (Shenoy, 1989).

Simultaneously with this effort of building solid state power amplifiers, great attention was also focused in the 1960s on GaAs as a semiconductor material due to its superior mobility, electron velocity and microwave properties. Over 10 years of R&D

have been spent on this semiconductor as a material for discrete field effect transistors (FETs). GaAs is now refined to a point where it is good enough for most analogue applications, with 4 inches diameter wafers already available in the market (Igi, 1988). It was realized right from the beginning that the T-R module architecture for phased arrays needs reduction in cost and size of these subsystems. This could only be guaranteed by replacing MIC with monolithic microwave integrated circuit technology. In MMIC all components, both passive and active, are incorporated into a single semiconductor die permitting complete operation by the application of DC and/or microwave signals. MMIC offers several advantages, the more important of them being (Chilton, 1987):

- a) It enables us to compress many separate functions into a single substrate and thus substantially reduce the severity of problems due to bonding and interconnects and improve reliability.
- b) The size and weight of the circuits are usually much smaller, allowing either subsystem size reduction or incorporation of more functions within the same volume.
- c) All circuit functions can be integrated so that highly reproducible performance can be obtained in batch production.
- d) Simpler packaging schemes can be considered owing to reduced circuit sizes.
- e) More than anything else, it is possible to achieve economical high volume production. Eventually the T-R module size is limited by the power output and the number of RF, DC and control line inter-connections.

It is thus evident that T-R module development is emerging as a business rather than a purely R&D effort with specific goals of making them available in the 1-30 GHz

region (Magarshak, 1988) These super components have been the subject of many studies and investigations (Naster, 1987 - Ladbroke, 1988) from the point of view of design, fabrication, production yield, process tolerance and cost. It is now certain that gallium arsenide monolithic microwave integrated circuit technology will be the technology vehicle through which the minimization of cost and enhancement of production yield and process tolerance are achieved. It has almost reached the status of a universal panacea, something that will solve all the problems that have been earlier confronted in the effort to achieve affordable phased arrays. In a very short period of time MMICs have progressed from a single function circuit to more complex multi-function modules, the emphasis being reduction of size and volume, higher rating for power devices and better efficiency for power amplifiers with gradual decrease in the cost of production. A comprehensive and detailed account of the progress made in T-R modules, as well as towards the realization of active aperture arrays, is provided by Pengelly (Pengley, 1989) and Shenoy (Shelnoy, 1989-1990) respectively. Ideally, the T-R module would contain amplifiers for transmit and receive states as well as for electronic phase shifting for both states. Thus it would carry out four RF functions, namely power amplification, phase shift/control, low noise amplification and switching. Because of the fact that the active aperture uses individual T-R module at the array radiating elements, this configuration can be substantially more efficient on the basis of overall prime power versus detection capability. For the same effective radiated power, the active aperture configuration can be smaller and lighter than the conventional system. A generic form of the T-R module is shown in Figure 2.

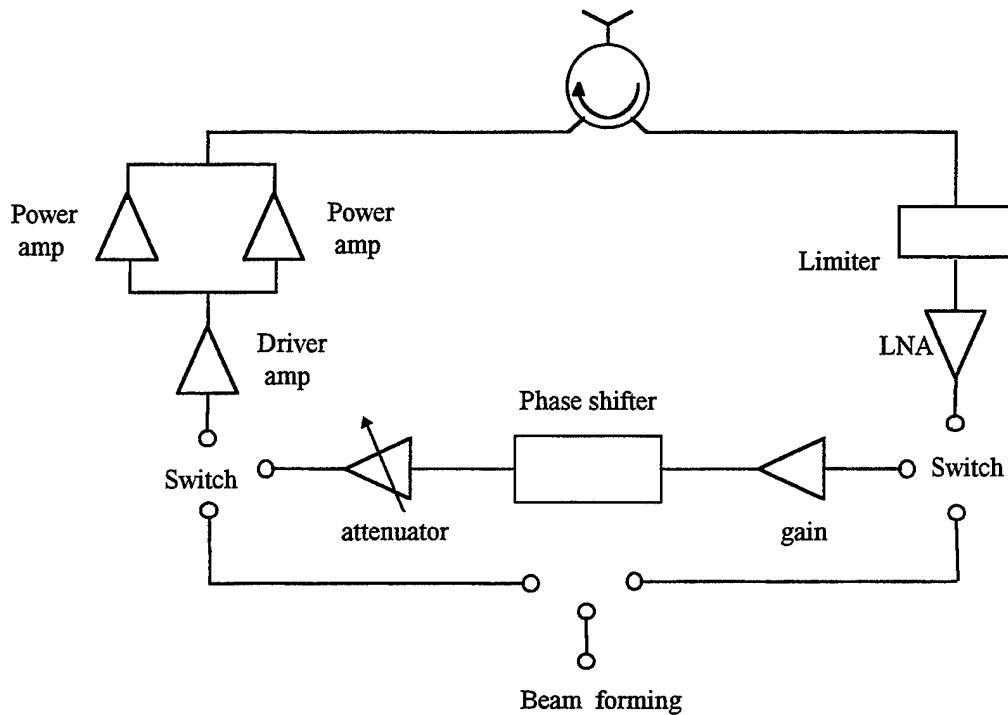


Figure 2. T-R module block diagram

Basically from the systems point of view the placement of the T-R module in the vicinity of the radiating element imposes constraints in respect to its circuit configuration.

Some of the more important ones are as follows (Sliva, 1988):

- a) The input microwave signal at the transmit channel of the T-R module would be in the region of a few nanoWatts. If the module has to provide output powers in tens of watts, then multistage power amplification will be necessary.
- b) The power dissipation at the T-R module would be primarily due to the power amplifier stages. To keep this at a low value, high efficiency modes of amplifier operation have to be used.

- c) Procedures for testing and calibration of the T-R modules will have to be accurate, simple, and economical.
- d) Variation of the output of the power amplifier will have to be achieved either through a resistive attenuator or by variable power or gain amplification without much loss of efficiency.
- e) The receive channel of the T-R module should have enough gain to offset the effect of likely post-LNA losses on the overall noise figure. In addition, since very little spatial filtering of the signal entering through the radiating element takes place, the LNA stages must have a high third-order intercept point. Since this can result in high losses in the order of watts in the LNA, trade-off studies with respect to noise figure, intercept point and power dissipation need to be carried out first.

From the point of view of cost, the key circuit functions are those of power amplification, low noise amplification and switching/control. These will determine the affordability of active phased arrays.

a) The Device

The active device most commonly used in GaAs MMIC is the field effect transistor using Schottky barrier gates (Norris, 1990). Three metal electrodes, namely gate, source and drain, are connected to a very thin $\approx 0.2 \mu\text{m}$ semiconductor active channel layer. The active channel is created beneath the gate by ion implantation of donor atoms into semi-insulating material or by growing epitaxial N-type GaAs on chromium doped semiinsulating GaAs substrate. Contacts to both source and drain is through ohmic metallisation. The gate is a Schottky barrier metal contact about $0.5\text{-}1.0 \mu\text{m}$ length so that

when a positive drain-source voltage is applied the current will flow. Thus, for small biases, the source-drain terminals behave like a linear resistor while for higher biases current saturation occurs. Since these devices are depletion mode FETs, on reverse biasing the gate, the active channel height as well as the source-drain current is reduced (Igi, 1988). The source-drain current flow can therefore be regulated by the bias applied to the gate electrode. Small voltages that are applied to the gate control large source-drain currents so that the FET can be considered as an amplifying device. On the whole, the GaAs FET has better noise performance, higher power gain per stage, and excellent thermal stability due to negative temperature coefficient of the drain current. However, in device design and in the selection of the technological processes, care has to be taken to minimize parasitic resistances and capacitances which limit the device performance (Knorr, 1995).

b) Power Amplifier

There are numerous reports on MMIC power amplifiers that have been developed for applications in phased array radars. Initially, the designs were mostly class A even though these did not lead to power efficiency higher than 40% (Kopp, 1989). In the last few years with improvements in FET chip design tuned-B, class-C operation has been realized with power efficiency higher than 50% (Bahl, 1989). This approach, which has been very successful at lower frequencies, can be incorporated in GaAs MMIC amplifiers to obtain higher power efficiency. High efficiency operation (Kopp, 1989) is achieved by controlling the harmonic loads presented to the transistor. This is, in essence, waveshaping of the voltage and current waveforms at the FET to reduce the overall power dissipation in the transistor. The FET in this case is operated close to the B-mode of

operation with a drain current waveform of a half rectified sine wave (Igi, 1988). The amplifier design provides a power match at the fundamental frequency, by tuning the output circuit to pass only the fundamental frequency. The second harmonic is presented with a short circuit to suppress second harmonic components in the voltage waveform. The short circuit can be achieved through a series resonance. The third harmonic is open-circuited to provide the proper component of third harmonic voltage under optimum RF drive conditions. The open-circuit impedance at third harmonic suggests a low pass topology for the fundamental matching circuit (Yamada, 1988). The increase in efficiency comes about as a result of the reduction of the time average of the voltage-current product at the FET. The amplifiers are usually fabricated in microstrip line configuration using semi-insulating GaAs substrates (Naster, 1987).

c) Phase Shifters

An equally critical and important constituent in the T-R module is the phase shifter. Silicon PIN diodes have been widely used for switching in phase shifters owing to their high performance (Bar-Lev, 1984). However, there is a shift in activity in this area towards the GaAs FET which not only offers total integrability with low noise amplifiers and power amplifiers, but also provides bi-directional switching with relatively low DC power requirements (Igi, 1988). Fast switching speeds (less than a fraction of a nanosecond), high power handling capability (greater than several watts), wide bandwidths, low power consumption, small size, low cost and light weight have enhanced the potential of FETs as microwave and millimeter-wave control devices (Bar-lev, 1989). The key parameter for design is the on-state resistance of the MESFET, which can be kept at low values by having heavily doped and thicker layers to minimize the gate periphery.

The performance requirements for the phasor network are narrow because of the need to obtain consistent gain and phase characteristics of the module. Phase shifting has been realized from one or more combination of any of the four phasor circuit techniques, namely, loaded line, reflection, switched line and high-pass/low-pass type (Kim, 1989). For small phase bits up to 45° phase shift, the loaded line phase shifter has been generally preferred because it provides a constant phase shift over a wide frequency range with a low VSWR. The reflection type phase shifter requires a hybrid coupler and appropriate reflection planes to achieve the desired phase shift. In the switched line phase shifter, phase delay is obtained by switching between two transmission paths of different lengths. For small as well as large phase shifts, the reflection type as well as the switched line type phase shifters are frequently employed (Jemison, 1990). These three types, however, use distributed line lengths needing relatively large substrate area, which would increase the cost of the phase shifter. The high-pass/low-pass switched combination phase shifter, on the other hand, dispenses with the distributed elements and therefore can be made compact as well as lower cost. Phase shifts are realized by switching the signal path containing either a high pass or low pass circuit (Herczfeld, 1988) . Therefore the design of this phase shifter is different because the MESFET can be used not only for switching but also for realization of high-pass/low-pass networks.

2. Feed and Control Network

The active aperture concept eliminates the need for a feed network for distributing large amount of RF power from a distant single source to the antenna aperture. Instead, because of the space combining aspect of RF power in these systems, the feed network deals with relatively low level signal distribution to and from the aperture. The feed and control network must, however, allow the passage of a variety of signals as follows (Carver, , 1981):

- a) RF signals of high stability in amplitude and phase for combining in space in the transmit mode and for coherent processing in the high performance Doppler processing mode.
- b) IF return signals with a dynamic range of at least 70 dB if down conversion is used at each array element.
- c) Digital signals at base band to control accurately phase and amplitude as well as to provide a timing reference at each active array element.

The requirements of excitation current for RMS sidelobe levels lower than 40 dB with pencil-beam electronically-steered arrays indicate that phase and amplitude control in the receive mode may have to be tight.

Thus each T-R module would need several microwave/RF lines, bias lines and digital lines to provide/process the data. This presents an extremely complex signal distribution network with topology and interference being quite severe, as thousands of T-R modules are involved. Signal interfaces at RF/IF and base band will be needed for each module and these may be provided from a centralized control or fully/partially distributed

control configurations. The best solution is the use of an optical fiber distribution network interconnecting the monolithically integrated optical components with the T-R modules, consisting of GaAs MMIC chips (Herczfeld, 1988). In this way, the conventional coaxial or waveguide distribution network is replaced by fiber optic links and the size and weight of the feed system is reduced by at least one order of magnitude. The merging of the microwave/millimeter wave techniques with light wave technology facilitates the introduction of such novel signal processing methods as wide band true time delaying for beam forming. Other desirable features of optical networks are high speed, good electrical isolation, elimination of grounding and immunity to electromagnetic pulses (Shenoy, 1990).

The three functions required to be accomplished by the optical feed network are: phase and frequency synchronization of the array, control signal distribution for beam forming and steering, and transmission of communication and data signals from a central processing unit to the T-R modules (Livne, 1989). These three tasks may be combined on the same fiber optic link or they may be transmitted as three different signals through different fibers. The basic building blocks of the feed network are: optical sources with facilities for modulation (microwave-to optical converter), fiber optic links and optical detector (optical-to-microwave down converter)/receiver (Seeds, 1988). These can be discrete components or form integrated optoelectronics having compatibility in production processes with the GaAs MMICs that form the T-R modules. Hence GaAs based integrated optoelectronic circuits appear to be the best bet for use in active aperture phased array systems.

a) Control Network

The requirements for phase and frequency synchronization of microwave signals is most stringent on the fiber optic link, and once these are met, the use of the link for control and communications signals in the active aperture array would be relatively easy. While the modulation frequency bandwidth and noise figure requirements for the link can be easily met, there are two mayor aspects for the requirements that need to be looked into before design (Livne, 1989). The first is the control architecture, i.e. whether control should be centralized or distributed or a hybrid scheme needs to be involved. The next is whether the control should be direct or indirect. If the control is indirect, the optical links transmits the control signals but the computations are carried out digitally and the control is implemented via the microwave elements. If the control is direct, the optical signals are used for phase shifting, and also for beam forming.

b) Power Supply Requirement Aspects.

One of the advantages claimed for active aperture phased arrays is that of graceful degradation. The random failure of individual T-R modules makes only undetectably minor changes to the radiation pattern of a large array. The losses in the transmitted signal in such cases reduce accuracy in estimation of target parameters in a very minor way and do not represent loss of total desired radar function (Brukiewa, 1992). However, very little has been mentioned about the effect of loss of a percentage of radiating elements due to power supply failures. In view of the graceful degradation characteristic of the active aperture phased arrays, the important reliability parameter in this case is the mean time between critical failures (MTBCF) rather than the MTBF. In an array of N T-R modules we define the array to have reached the critical failure stage when

q of the T-R modules are out of action as a result of which either the power gain of the antenna has fallen below an acceptable value or the sidelobe levels have gone beyond an acceptable level (Elliot, 1985). On the other hand the MTBF in this case is the average time taken for any single T-R module to be out of service from this ensemble of N T-R modules. If the entire system is being supplied by only one power supply unit with an MTBF of T , the MTBCF is the same as the MTBF because the failure of the power supply unit results in total failure of the array. In reality, the use of a centralized power supply for all the T-R modules is not recommended because it has to generate very high currents at low voltages and distribute the DC supply to all modules across the antenna aperture (Claridge, 1989). By and large, it is therefore advisable to have independent power supplies for individual T-R modules or parallel the output of these individual power supplies for each sub-array with an over-capacity. The percentage of over capacity is maintained at a value slightly higher than the percentage of T-R module failures that determine the critical failure of the array. The power requirements of a single T-R module can be conveniently obtained from compact and highly reliable units as the present state of the art in power supplies indicates that power densities in the region of 50 W/in^3 are possible (Chilton, 1987).

3. Antenna and T-R Module Coupling

In the design of active aperture arrays, the mechanical structure, thermal management, module replacability and size constraints are interdependent factors unlike the situation in conventional phased arrays. Generally speaking, active phased array

designs can be classified into two configurations, which are referred to as “tile” or “brick” configurations (Claridge, 1989). The tile concept places the GaAs circuits on the same plane as the patch radiator. Hence the available aperture space is shared between the radiating elements and the circuits of the T-R modules. Figure 3 is a schematic of such an arrangement. The patch radiators in this case can be edge-fed by microstrip lines. Schaubert, in (Pozar and Schaubert, 1984) have pointed out a number of problems of using this approach. Firstly a single layer substrate will not have for all frequency bands enough surface area to accommodate radiating elements, phase shifters and feed networks without crowding and without generating deleterious coupling between active circuitry and radiating elements. Since the antenna element spacings are in the region of half wavelength, to avoid grating lobes, even at C-band, the routing of the feed network and the bias lines becomes a serious problem. Hence closer spacing of antenna elements is ruled out, thereby limiting the maximum scan range of the array (Claridge, 1989).. This configuration can also give rise to severe spurious feed radiation (Galanti, 1993).

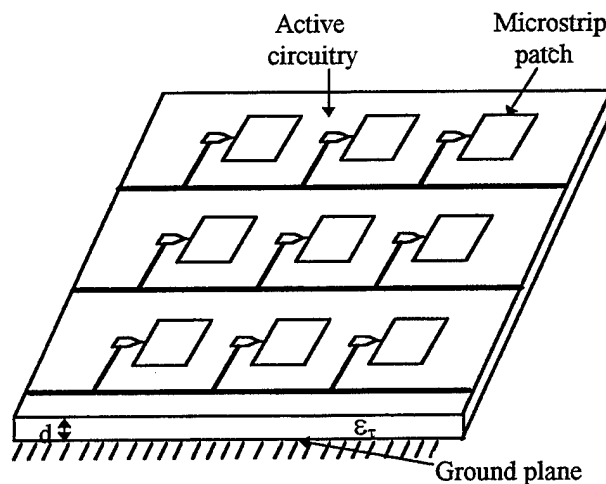


Figure 3. Patch array layout

The brick configuration provides a way out of this situation by removing the active circuits, phase shifters, etc. away from the same plane as the radiating elements. Figure 4 shows one arrangement which is in one sense a two-layer design (Pengelly, 1989). Here a grounded layer of GaAs holds the active devices and the feed network and a cover layer of a low dielectric constant material holds the radiating elements. Coupling from the feed to the antenna elements is made by holes or by proximity coupling. This configuration doubles the usable substrate area and also provides substrates matched to the distinct electrical functions of radiation and circuitry. The dielectric constant of the antenna substrate being lower than the GaAs used for the feed substrate, the movement of the scan blindness angles towards broadside is effectively eliminated in this case (Kitchener, 1987). In this configuration spurious signal radiation from the feed substrate has not been fully eliminated. On the other hand, spurious radiation from the feed may be more harmful because the strong coupling to the radiating element directly above.

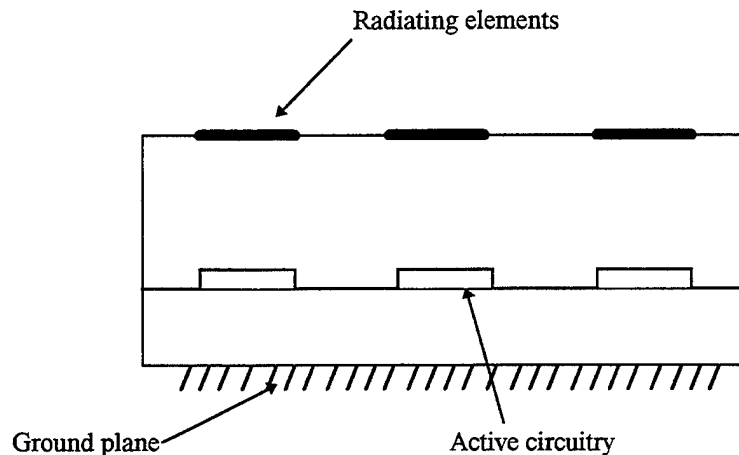


Figure 4. Two-layer feed system

D. MANUFACTURABILITY AND COST

As GaAs MMIC technology matures and these chips become readily available there will be increasing demands on improving the performance in production to bring down the cost. It can be readily seen that, since the typical processing sequence in the case of T-R modules uses several semiconductor technologies, high volume applications benefit most from cost considerations. To meet the low cost objective, the process must start at the design stages, where the emphasis would be to avoid physically large and low yield circuits as well as extremely complex circuit designs which are likely to result in low yield.

Specifically, some of the design considerations for high yield low cost T-R modules can be spelt out as follows (Borkowski, 1989):

- a) Power amplifiers should generate high levels of power output with high efficiencies. Hence;
 - 1) The load impedance presented to the final device needs to be carefully chosen to maximize power output and efficiency.
 - 2) Since losses in the output circuit of the final stage significantly affect power output and efficiency, off-chip matching may be necessary to minimize losses.
 - 3) Since GaAs is a poor thermal conductor, heat sinking of the chip is mandatory, the trade-off being amplifier size and weight.
 - 4) For efficient multiple stage designs the final stage of the amplifier should reach saturation before the preceding stages.

b) The use of MESFETs as switching elements in the T-R module imply that they should have high isolation and low insertion loss. Therefore;

1) The FET design should keep the off/on resistance ratio as high as possible.

The trade-off in this case is between short gate length (hence lower processing yield) and insertion loss (channel length largely determines the on resistance as well as insertion loss).

2) The value of the parasitic drain-source capacitance affects the off-state isolation. This capacitance largely depends on the source-drain spacing of the FET.

c) Low noise amplifiers require high gain, low noise figure and linearity. Hence;

1) Multiple-stage linear designs require proper device sizing of successive stages to maintain low inter-modulation distortion products. The trade-off is higher dissipated power for better linearity.

2) Circuit losses at the input before the first stage degrade the noise figure. Since thin transmission lines on GaAs substrate tend to be lossy, off-chip matching may be more suitable.

3) A low noise condition requires biasing close to the pinch-off voltage of FET. Both gain and noise figure are highly dependent on the pinch-off voltage when the biasing is close to pinch-off. Since pinch-off voltage varies significantly for devices on the same substrate, the bias condition has to be chosen carefully. Thus gain and noise figure are to be traded off against repeatable performance.

d) Phase shifters require consistent phase and amplitude response in all the states.

They are also required to be compact and less sensitive to process variations.

Thus phase shifter designs would generally be high-pass/low-pass filter network switched phase bit configurations with lumped elements for the networks.

III. RADAR PARAMETERS AND DESIGN

This chapter describes the development of the Radar Range Equation related to the Active Phases Array and a description of the main parameters involved in such equation for further system performance assessment. At the same time, this chapter will describe two of the main radar functions such are the search and track in an active phased environment.

A. RADAR

Radar is an electromagnetic system for the detection and location of objects. It operates by transmitting a particular type of waveform, such as a single pulse. An elementary form of radar consist of a transmitting antenna emitting electromagnetic radiation generated by an oscillator of some sort, a receiving antenna, and a energy-detecting device or receiver. A portion of the transmitted signal is intercepted by a reflecting object (the target) and is re-radiated in all directions. It is the energy re-radiated in the direction of the receiving antenna that is of prime interest to the radar. The receiving antenna collects the returned energy and delivers it to a receiver, where it is processed to detect the presence of the target and to extract it's locations and possible it's relative radial velocity. The distance to the target for a monostatic radar is determined by measuring the time taken for the radar signal to travel to the target and back. Radio waves travel at 328 yards. every millionth of a second, which means that every microseconds represents 164 yards. of range.

The echo returned to the radar by a simple, point-source target will be an exact reproduction of the transmitted signal, shifted in time by an amount corresponding to the range delay and shifted in frequency by the “Doppler shift” due to the target relative radial velocity (Eaves, 1987).

1. The Radar Equation

The radar range equation, or simply the radar equation, is the single most descriptive and useful mathematical relationship available to radar designers and researchers. In its most complete form, the radar equation accounts for not only the effects of each major parameter of the radar system but also those of the target, target background, and the propagation path and medium. Thus, one can use the radar equation to conduct performance assessments and cost studies based on various parameters and scenario trade-off or conditions for the radar, target, and environment.

Let’s turn our attention to a radar problem. Suppose an airplane is the radar target as shown in Figure 5.

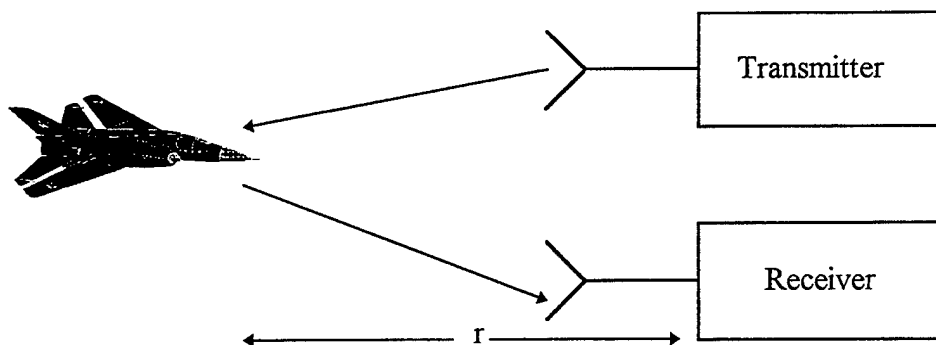


Figure 5. Radar example

We will assume that the transmit and receive antennas are pointed such that the pattern maxima are directed toward the target (directional antenna that has a power gain G_t). The power density (P_d) incident on the target is then:

$$P_d = \frac{P_t}{4\pi R^2} G_t \quad (\text{Eq. 1})$$

The propagating EM wave beam will strike the target and, as a result, the incident energy will be scattered in various directions. Some of the energy will be reflected in the direction of the radar, and this is determined by the power density of the target and the σ target's backscatter radar cross section (RCS). σ is a measure of the target's ability to reflect EM waves, and its value is expressed in area. A target's backscatter RCS is defined as 4π times ratio of the power per unit solid angle reflected by the target in the direction of the illuminating source (radar) to the power per unit area of the incident wave at the target. Then, the Power Density of this reflected signal (echo) as it reaches the radar is given by:

$$P D_r = \left(\frac{P_t G_t}{4\pi R^2} \sigma \right) \frac{1}{4\pi R^2} \quad (\text{Eq. 2})$$

The power received by the radar P_r , is determined by the effective capture area A_e of the receiving antenna, as shown in Figure 6 and is given by:

$$P_r = \frac{P_t G_t \sigma}{(4\pi)^2 R^4} A_e \quad (\text{Eq. 3})$$

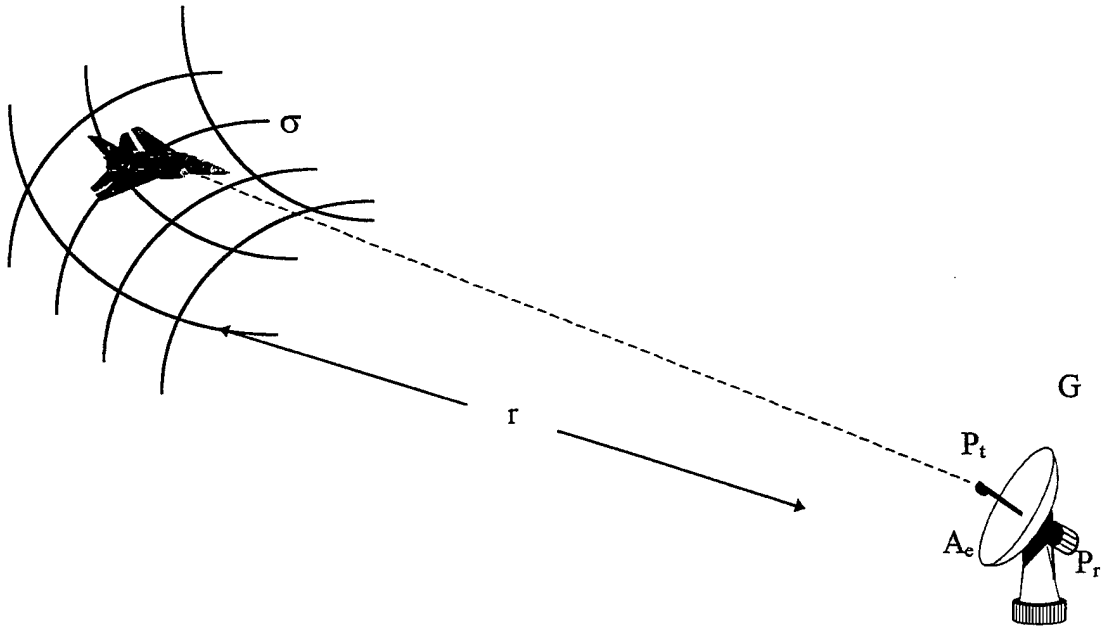


Figure 6. Power received by radar due to target located at range R and with RCS σ .

Let's recall that the antenna gain is the amount of radiation an antenna concentrates in a given direction to what would have been obtained if the antenna had not been used and is related to the effective capture area by:

$$G = \frac{4 \pi A_e}{\lambda^2} \eta_g \quad (\text{Eq. 4})$$

where λ is the wavelength of the electromagnetic wave and η_g is the antenna gain efficiency. Then, substituting for A_e , we have

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4 \pi)^3 R^4 \eta_g} \quad \text{in W} \quad (\text{Eq. 5})$$

and for radars that employ the same antenna for both transmission and reception like the Active Phased Array Radar, the radar equation becomes:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 \eta_g} \text{ in W} \quad (\text{Eq. 6})$$

For more accurate and realistic performance predictions, one must account for the effects of (Eaves, 1987):

1. The propagation medium and path.
2. Atmospheric noise.
3. System losses.
4. Thermal noise induced within the radar.
5. Signal processing losses .
6. Other losses associated.

Finally, and taking into account all the parameters written above, the maximum range of the radar will be determined by the minimum received power that can be detected (Sabatini, 1994) so:

$$R_{\max} = \left[\frac{P_t G A_e \sigma E(n)}{(4\pi)^2 K T_0 F L_{se} (SNR_n)} t_0 \right]^{1/4} \quad (\text{Eq. 7})$$

where

P_t is the transmitted power in watts,

G is the antenna gain,

A_e is the effective antenna aperture in m^2 ,

σ is the target radar cross section (RCS) in m^2 ,

$E(n)$ is a factor (≤ 1), depending on n , which takes into account the integration losses,

t_0 is the time-on-target in seconds,

K is the Boltzman's constant which value is 1.38×10^{-23} J/K,

T_0 is the standard temperature, which is 290° K,

F is the receiver noise figure,

L_{sc} is the total loss contributions (receiving losses, transmitting losses, atmospheric losses, and beamshape losses, and

SNR_n is the received signal-to-noise ratio resulting from integrating n pulses.

2. The Searching Function

Searching by far, is the most common function of radars employed in military and civilian radars. This is, search a large volume of space and locate the position of targets within the search coverage.

The target reports generated by the searching function can be processed to form target tracks. When this radar data processing tracking function is performed by the radar, the overall radar is usually called a tracking-while-scan (TWS) radar (Schelher, 1980). The target-tracking vectors formed in the system allow the absolute motion characteristics of the target to be determined. The motion characteristics of the target can then be used to determine the relative threat posed by the target and also to predict the future position of the target.

Some key factors which determine the parameters of the searching function are: Detection Range, Range and Doppler Resolution, Data Rate, Tracking Accuracy, Azimuth Beamwidth, Average Transmitted Power, Effective Antenna Aperture, Effective Pulsewidth, Dwell Time on target, and Transmitter Frequency among others. Perhaps the most important design feature of the searching function is its detection range. This requirements sets the relative size and complexity of the radar, which, in turn, determines its cost. It is convenient to examine this requirement by assuming that the radar functions in a free space without the effects of surface and weather clutter, atmospheric or weather attenuation, external electromagnetic interference, etc. and this can be a good theme for future thesis researches.

3. The Tracking Function

The tracking function is the one that provides the information which allows the weapon to engage and destroy targets. The design of this function is influenced by a number of factors such as the weapon range and coverage volume, type of weapon guidance, weapon kill mechanism and effectiveness, rate of fire, number of targets to be engage, and the purpose of the weapon system.

This radar function generally requires a good resolution and precise measurement of target position (angular accuracy). The ability to make a precision target-position measurement depends on the basic radar-resolution capability and the signal to noise ratio (Schelher, 1986). A high transmitter frequency leads to narrow antenna beamwidths and the ability to transmit wide bandwidths. This results in higher radar resolution, leading to

the conclusion that the transmission frequency of tracking radars will be found in the higher radar frequency bands (S band and above).

The signal-to-noise ratio can be maximized by both increasing the transmitted frequency which in turn increases the antenna gain, and also increasing the time the antenna tracks the target thereby collecting more target energy.

Some of the key factors which determine the detailed radar tracking function are: Detection Range, Clutter Performance, Range and Doppler Resolution, Low-Angle Tracking, Tracking Accuracy, Average Transmitter power, Effective Antenna Aperture, Effective Pulsewidth, System Noise Temperature, Azimuth Beamwidth among others.

4. Radar Functions Dependencies.

There are some basic differences between the searching and the tracking function in an Active Phased Array Radar. The most significant factor is that, to a first order, the detection range of the searching function is independent of the transmitter frequency, while that of the tracking function improves as the frequency is increased. The reason for the improvement of tracking function with frequency is that the antenna gain is directly increased with frequency, thereby focusing more power on the target. This increased power is collected for a time which is inversely proportional to the bandwidth of a servo control loop (Acher, 1975), thereby resulting in increased target energy for increased transmitter frequency. For the searching function, this increased power is collected for a proportionally shorter time, since the radar must search more cells in the same time due to the narrower antenna beamwidth. The net result is that the target energy collected by the

searching function is, to a first order, constant with transmitter frequency. As frequency is increased, atmospheric attenuation and weather attenuation become significant, and hence must be included in any consideration of operating frequency.

5. Angular Accuracy as the Key.

The key of the tracking function is to provide accurate target position information. This information is measured by the radar whose outputs are in the form of estimates in spherical coordinates (range, azimuth, and elevation angles). The ability of the tracking function to estimate the target's position is related to a number of factors, which include the characteristics of the radar, the environment in which the radar works, and errors that are induced by the target itself. We have already discussed the importance of the radar's resolution capability as the starting point in position measurement and the role of the signal-to-noise energy ratio, which determines to what degree the resolution cell can be split or interpolated to achieve finer accuracy. The angular error is range dependent and that the radar resolution and angular noise-related errors primarily come into play at long range. This is sometimes referred to as the precision of the radar to distinguish this quantity from the resolution, which relates to the radar's ability to separate multiple targets. At some intermediate range, the instrumental error or inherent accuracy of the radar dominates. This factor relates to the accuracy with which the output data represents the actual position of the radar beam and includes mechanical and sensor errors. At short ranges, angular errors are target-induced, caused by target glint (shifting of the apparent center of target reflection) and target dynamics (servo lag due to target motion) (Barton,

1976). The overall accuracy of the tracking performance as a function of range is a composite of all components of angular error.

The accuracy of the tracking function is generally applicable at elevation angles greater than several radar beamwidths above the horizon. As the target moves closer to the horizon (into the low angle region), reflections from the surface cause multipath returns. The conventional radar tracker accepts both the direct return and the multipath return that comes from a direction which corresponds to the apparent image of the target (Lloyd's mirror effect) located below the surface. When the multipath reflection is small in magnitude (due to either antenna sidelobes or a low surface reflection coefficient), a small but significant error occurs. When the multipath reflection is large, which corresponds to targets within a radar beamwidth of the horizon, angular errors are large and loss of tracking may occur.

Several solutions have been proposed and tested which allow radars to track into the low angle region but this also can be a good Thesis Topic for future NPS students.

6. Maximum Radar Range Performance and the Angular Accuracy Relationship in the Active Phased Array Radar Tracking Function.

As I said before, the angular accuracy (σ_ε) is another parameter in which the radar system depends on and it's probably the most important requirement in the tracking function. For a monopulse antenna, the angular accuracy is defined in (Sabatini, 94) as:

$$\sigma_\varepsilon = \frac{\Delta \alpha}{K_g \sqrt{2 SNR_n}} \quad (\text{Eq. 8})$$

where

$\Delta \alpha$ is the one dimensional antenna beamwidth and,

K_g is a gradient of the difference beam in the monopulse antenna configuration and is usually a constant value.

Furthermore, $\Delta \alpha$ is directly related to the solid beamwidth ($\Delta \Omega$) when the beam has a pencil beam form in the following way:

$$\Delta \Omega = \frac{\pi}{4} (\Delta \alpha)^2 \quad (\text{Eq. 9})$$

Forgetting the one dimension equation and taking into account the two angle coordinates, we can show the angular accuracy as follows:

$$\sigma_\varepsilon = \frac{1}{K_g} \sqrt{\frac{2 \Delta \Omega}{\pi (SNR_n)}} \quad (\text{Eq. 10})$$

or

$$SNR_n = \frac{2 \Delta \Omega}{\pi (K_g \sigma_\varepsilon)^2} \quad (\text{Eq. 11})$$

which transforms the maximum radar range performance equation for a tracking Active Phased Array Radar to:

$$R_{\max} = \left[\frac{P_t G A_e \sigma E(n) (K_g \sigma_\varepsilon)^2 U_T}{16 \pi K T_0 F L_{se} (2 \Delta \Omega)} t_0 \right]^{1/4} \quad (\text{Eq. 12})$$

where U_T is the utilization factor which is defined as the fraction of frame time spent in tracking.

IV. SYSTEM PERFORMANCE ASSESSMENT

This chapter describes the assessment program that is going to be implemented in a Microsoft Excel 5.0 spread sheet environment and is based on a few estimated and determined radar parameters described in Table 1 and Table 2. All those parameters are consider estimated.

This implemented program will use links and functions to determine those radar parameters, and the maximum range performance (R_{max}) of the Active Phased Array Radar as shown in Table 3. So, whenever one estimated parameter is changed manually, the final maximum range prediction will automatically show the newest calculation in the result.

As we will see, this is a simple program that can be run in any compatible spread sheet environment such as Lotus, Q-Pro, etc.

A. ESTIMATED RADAR PARAMETERS

The estimated parameters shown in Table 1 are explained in the following manner:

1. The estimated Frequency of transmission f assumed is 10 GHz for the X Band.
2. The estimated Antenna Height A_h assumed is 0.6 meter.
3. The estimated Antenna Width A_w assumed is 0.72 meters.
4. The estimated Scan Elevation angle ϵ is between $\pm 60^\circ$.
5. The estimated Scan Azimuth angle Ψ assumed is 120° span.
6. The estimated Total number of TR modules for this APAR assumed is 700.
7. The estimated Angular Accuracy required is assumed to be 0.3 mrad.

Frequency (GHz)	(f)	10
Antenna Height (m)	(A _h)	0.5
Antenna Width (m)	(A _w)	1
Scan elevation max.(+/-deg)	(ε)	60
Scan azimuth max.(deg)	(Ψ)	120
Total No. of TR modules	(N _{TR})	700
Required Angular Accuracy (mrad)	(σ _s)	0.3

Table 1. Estimated Radar Parameters

B. DETERMINED RADAR PARAMETERS

The determined radar parameters shown in Table 2 are explained in the following manner:

1. The Coverage Solid Angle Ω is the product of the azimuth angle Ψ and the elevation angle ε [Ref. 30:p. 567], then,

$$\Omega = \Psi \sin \varepsilon \quad (\text{Eq. 13})$$

which means that if the elevation angle or the azimuth angle or both change, the coverage solid angle will also change automatically in Table 2 when the program runs.

2. The Antenna Aperture A_e is the product of the antenna height and the antenna width, then,

$$A_e = A_h A_w \quad (\text{Eq. 14})$$

which means that if the antenna physical parameters change, the antenna aperture will also change automatically in Table 2 when the program runs.

3. The Average Power P_{av} is assumed to be 2 watts because tapering arrangement of high low TR modules was not known.
4. The Total Transmitted Average Power P_t is the product of the average power and the number of T-R modules, then,

$$P_t = P_{av} N_{TR} \quad (\text{Eq. 15})$$

5. The Radar Cross Section σ is listed as a small target of 0.6 m^2
6. The antenna wavelength λ is the ratio between the EM wave propagation speed c ($3 \times 10^8 \text{ m/sec}$) and the frequency f in Hz, then,

$$\lambda = \frac{c}{f} \quad (\text{Eq. 16})$$

7. The 3-D beamwidth $\Delta\Omega$ is also derived and is defined as:

$$\Delta\Omega = \frac{\lambda^2}{A_e} \quad (\text{Eq. 17})$$

8. The 1-D beamwidth $\Delta\alpha$ is derived from equation (Eq. 9), then,

$$\Delta\alpha = \sqrt{\frac{4 \Delta\Omega}{\pi}} \text{ in degrees.} \quad (\text{Eq. 18})$$

9. K_g is a gradient of the difference beam in the antenna and is assumed to be 1.58 in this assessment.
10. As we recall in equation (Eq. 11), the signal-to-noise ratio SNR_n is defined as:

$$SNR_n = \frac{2 \Delta\Omega}{\pi (K_g \sigma_s)^2}$$

and can also be determined when the probability of detection and probability

of false alarm are known using some related published technical tables.

11. The antenna gain efficiency η_g is assumed 60%, so the antenna power gain can be easily determined automatically by using (Eq. 4).

$$G = \frac{4 \pi A_e}{\lambda^2} \eta_g$$

12. The integration loss factor $E(n)$ associated with n multiple pulses detection is assumed to be -1 dB.
13. The frame time t_{so} is the time dedicated to every function in the radar system such as search, track, and auxiliary task (Sabatini, 1989). This is assumed to be 3 seconds for this APAR system and is equal to the time-on-target t_o because only the tracking function is taking into account.
14. The fraction of radar time U is consider normalized to 1 and is the sum of the fraction of radar dedicated to search U_s , the fraction of time for track U_t , and the fraction of time for auxiliary tasks U_a (Sabatini, 1989).

In this case we assume that all the frame time is dedicated to the track function, so only U_t is considered, then

$$U_t = 1 - U_s - U_a \quad (\text{Eq. 19})$$

15. The total loss L_{se} is the sum of all the losses considered in the TR modules, the RF combiner, and the baseband processing. For this case, we assume:
 - a) Atmosphere loss L_A due to moisture absorption is 1.5 dB.
 - b) Beam pointing loss L_θ due to beam pattern variation in the aperture is 0.3 dB.

- c) Transmitter loss L_T due to circulator and transmission line in transmitter is 2 dB.
 - d) Receiver loss L_R due circulator and transmission line loss in receiver 2 dB.
 - e) Scan angle loss L_G due to the scan angle variation of antenna gain is 2 dB.
 - f) Processing loss L_X due baseband detection loss from signal processing 2 dB.
16. kT_0 is the product of the Boltzman constant k (1.38×10^{-23} J/K) and the standard temperature T_0 (290°) and is expressed as -204 dB in round numbers.
17. F is the receiver noise figure and is assumed to be 4 dB.

Then, for Table 2 we have:

Coverage Solid Angle, Ω (rad)	
SIN(elevation angle)	0.866025
$\Omega=2*(\text{azimuth angle}) * \text{SIN}(\text{elev angle})$	3.627599
Antenna Aperture $A_e(\text{m}^2)$	0.5
Ave. Power P_{AV}	2
Total Transmitted Average Power (watts)	1400
Target characteristics, σ (m^2)	0.6
Antenna Wavelength, λ in m	0.03
3D Beamwidth, $\Delta\Omega$	0.0018
1D Beamwidth, $\Delta\alpha$ (deg.)	2.742925
Gradient beam K_g	1.58
Signal to Noise Ratio SNR_n	5100.303
Antenna Gain Efficiency η_g	0.6
Antenna Power Gain, G	4188.79
Integration loss $E(n)$ in dB	-1
Frame time, t_{so} in sec	3
Fraction of Time for Tracking, track only assumed, U_t	1
Atmosphere loss in dB	1.5
Beam pointing loss in dB	3
Transmitter loss in dB	2
Receiver loss in dB	2
Scan Angle loss in dB	2
Processing loss in dB	2
Total loss, L_{se} in dB	12.5
Boltzman Product (KT_o) in dB	-204
Noise Figure F in dB	4

Table 2. Determined Radar Parameters

C. MAXIMUM RANGE PERFORMANCE

The Maximum Radar Range as described in equation (Eq. 12) is:

$$R_{\max} = \left[\frac{P_t G A_e \sigma E(n) (K_g \sigma_\varepsilon)^2 U_T}{16 \pi K T_0 F L_{se} (2 \Delta \Omega)} t_0 \right]^{1/4}$$

With all the parameters previously known, the Table which describes the radar performance is as follows:

Maximum Range Performance Assessment	
Ave. Transmitted Power, P_{av} (dB)	31.46128
Antenna Gain, G	36.220886
Antenna aperture, A_e (dB)	-3.0103
RCS of target, s (dB)	-2.218487
Integration loss, $E(n)$ (dB)	-1
Gradient beam K_g	3.9731417
Req. Angular Accuracy σ_ε in mrad	-70.45757
Utility factor for track, U_t (dB)	0
Frame time, t_{so} (dB)	4.7712125
$(16 * \pi)$ (dB)	-17.0127
Boltzman's product, KT_0 (dB)	204
Noise Figure, F (dB)	-4
Total Track loss, L_{se} (dB)	-12.5
3D Beamwidth * 2, $(2\Delta\Omega)$ (dB)	24.436975
	194.66443
Max. Range Assessment, R_{\max} (Km)	73.554775

Table 3. Maximum Range Performance Assessment

V. CONCLUSIONS

This Thesis developed a MS. Excel 5.0 spread sheet to evaluate the Maximum Range Performance in an Active Phased Array Radar which makes it easy to assess the radar performance for different parameters.

Without any doubt, the most effective way of improving the detection range would be to increase the number of T-R modules in a filled active aperture array. This is because, unlike in a passive aperture system, the number of T-R modules affects the RF power available to transmission as well as the gain of the antenna. Some constraints of physical aperture and beamwidth considerations can restrict the increase of the number of T-R modules. If however the average power is taken into consideration, the product of the number of T-R modules and the Average Power will give us the transmission power. Based on a judicious mix of increasing the Number of T-R modules and the average power, the detection range can be improved. The requirement of an appropriated angular accuracy is the other factor that affects the improvement of the radar detection and is proportionally related to it. The more the angular accuracy, the better achievable detection range.

From all this work, it is necessary to mention the fact that, the maximum detection range of the Active Phased Array Radar is directly dependent on the number of T-R modules. In order to proliferate active aperture systems, reducing the cost of T-R modules in production is an important consideration. The T-R modules is therefore a key subsystem for Active Phased Array Radars.

This Thesis has also analyzed the main principles of Active Phased Array Radars from the tracking point of view. Phased Array Radars can use either passive or active apertures and in the active aperture approach, each array element contains a transmitter and a low-noise receiver; this transmitter is usually a solid-state amplifier device which tends to favor frequencies at L band or below where reasonable efficiencies can be achieved. An advantage of this system is that these radars exhibit rapid beam agility for accurately tracking many targets while scanning the search volume simultaneously.

In surveys of modern military radars, Active Phased Array Radar has been described as providing the ultimate performance but at high cost. Thus both, the economics and the performance must be given consideration in any design of Active Phased Array Radar. In general, those APAR's meet performance requirements that are difficult or impossible to meet by any other way. Economic considerations have forced design compromises which affect the coverage, frequency selection, and the overall performance of the radar. Even with these design compromises, Active Phased Array Radars are still expensive, which has tended to limit its large-scale production. With present microwave technology, array costs are measured in hundreds of dollars per element but monolithic technology is expected to reduce this cost to under a hundred dollars per element.

Another advantage of the Active Phased Array Radar is its energy- management ability, whereby it can concentrate maximum energy on critical targets while dwelling for shorter times on non-critical targets without wasting energy in sectors where there are no targets or those of limited interest. This energy management ability optimizes the target-tracking function of the phased array and is unique when coupled with a semi-active

missile guidance system, which requires a high rate of target illumination during its terminal phase.

In addition to the target-tracking function, Active Phased Array Radars can also provide a target-acquisition function, a search function, and a target-illumination function for semi-active missile guidance. The principal advantage of this multifunction operation is that the large investment in the phase array antenna and the associated overhead computer and processors is spread over all the requirements.

APPENDIX

This appendix contains the Microsoft Excel 5.0 codes for all the spread sheets implemented for System Performance Assessment.

For Table 1. Estimated Radar Parameters

(Sheet X)

	A	B
1		
2		
3		
4	Frequency (GHz)	"ASSUMED VALUE"
5	Antenna Height (m)	"ASSUMED VALUE"
6	Antenna Width (m)	"ASSUMED VALUE"
7	Scan elevation max.(+/-deg)	"ASSUMED VALUE"
8	Scan azimuth max.(deg)	"ASSUMED VALUE"
9	Total No. of TR modules	"ASSUMED VALUE"
10	Req. Angular Accuracy in mrad	"ASSUMED VALUE"

For Table 2. Estimated Radar Parameters

(Sheet Y)

	A	B
1	Coverage Solid Angle, Ω (rad)	
2		
3	SIN(elevation angle)	=SIN(PI()/180*X!B7)
4	$\Omega=2*(\text{azimuth angle}) * \text{SIN (elev angle)}$	=2*PI()/180* X!B8*B3
5		
6	Antenna Aperture (m^2)	=X!B6* X!B5
7		
8	Ave. Power (high pwr + low pwr modules)	"ASSUMED VALUE"
9	Total Transmitted Average Power (watts)	=B8*X!B9
10		
11	Target characteristics, σ (m^2)	"ASSUMED VALUE"
12	Antenna Wavelength, λ	=300000000/(X!B4*1000000000)
13	3D Beamwidth, $\Delta\Omega$	=B12*B12/B6
14	1D Beamwidth, $\Delta\alpha$ (deg.)	=180/PI()*SQRT(4*B13/PI())
15	Gradient beam K_g	"ASSUMED VALUE"
16	Signal to Noise Ratio SNR_n	=2*B13/(PI()*B15*X!B10*0.001*B15*X!B10*0.001)
17	Antenna gain efficiency, η_g	"ASSUMED VALUE"
18	Antenna Power Gain, G	=4*PI()*B6*B17/(B12*B12)
19	Integration loss in (dB)	"ASSUMED VALUE"
20	Frame time, t_{so} (sec)	"ASSUMED VALUE"
21	Fraction of Time for Tracking, track only assumed, U_t	"ASSUMED VALUE"
22		
23	Atmosphere loss in dB	"ASSUMED VALUE"
24	Beam pointing loss in dB	"ASSUMED VALUE"
25	Transmitter loss in dB	"ASSUMED VALUE"
26	Receiver loss in dB	"ASSUMED VALUE"
27	Scan Angle loss in dB	"ASSUMED VALUE"
28	Processing loss in dB	"ASSUMED VALUE"
29	Total loss, L_{se} (dB)	=SUM(B23:B28)
30		
31	Boltzmann's Product (KT_o) in dB	"ASSUMED VALUE"
32		
33	Noise Figure in dB	"ASSUMED VALUE"

For Table 3. Maximum Range Performance Assessment.

(Sheet Z)

	A	B
1	Maximum Range Performance assessment	
2	Ave Transmitted Power, P_{av} (dB)	=10*LOG10(Y!B9)
3	Antenna Gain, G	=10*LOG10(Y!B18)
4	Antenna aperture, A_e (dB)	=10*LOG10(Y!B6)
5	RCS of target, σ (dB)	=10*LOG10(Y!B11)
6	Integration loss, $E(n)$ (dB)	=Y!B19
7	Gradient beam K_g	=2*10*LOG10(Y!B15)
8	Req. Angular Accuracy in mrad	=2*10*LOG10(X!B10*0.001)
9	Utility factor for track, U_t (dB)	=10*LOG10(Y!B21)
10	Frame time, t_{so} (dB)	=10*LOG10(Y!B20)
11	(16* pi) (dB)	=-LOG10(PI()*16) *10
12	Boltzmann product , KT_o (dB)	=-Y!B31
13	Noise Figure, F (dB)	=-Y!B33
14	Total Track loss, L_{se} (dB)	=-Y!B29
15	3D Beamwidth * 2 (dB)	=-10*LOG10(2*Y!B13)
16		=SUM(B2:B15)
17		
18		
19	Max. Range Assessment, R_{max} (Km)	=POWER(10,B16/40)/1000

LIST OF REFERENCES

1. ACKER, A.: *"Basic Fundamentals and Applications of Radars."* Varian Associates, 1975.
2. AMITAY, N., GALINDO, V.: *"Theory and Analysis of Phased Array Antennas."* Wiley Interscience, NY, 1972, Chap. 5.
3. BAHL, I. L., and BURKIEWA, T. F.: *"Class C Amplifier Manufacture."* IEEE Trans, 1989.
4. BAR-LEV, A.: *"Semiconductors and Electronic Devices."* Prentice Hall, 1984.
5. BARTON, D. K.: *"Low-Angle Tracking."* Microwave Journal, Dec. 1976, pp. 14-24.
6. BILLAM, E. R.: *"New Technologies in Phased Array Radar."* Proc. Military Microwaves, MM-85, pp. 57-66.
7. BILLETER, D.: *"Multifunction Array Radar."* Artech House, Boston, USA, 1989.
8. BORKOWSKI, M. T., and LAIGHTON, D.G.: *"Decreasing Cost of GaAs MMIC Modules is Opening Up New Areas off Application."* Electronic Progress, 1989, XXIX.
9. BROOKNER, E.: *"Radar Technology."* Artech House, Boston, USA, 1979.
10. BRUKIEVA, T.: *"Active Arrays: The Key to Future Radar Systems Development."* Journal of Electronic Defense, Sep 1994.
11. CARVER, K. R., and MINK, W. J.: *"Microstrip Antenna Technology."* IEEE Trans., 1981, pp. 1-24.
12. CHI, J.: *"High Performance Monolithic Power Amplifier using all RIE Fetch Process."* IEEE GaAs IC Symposium Digest, 1987, pp. 159-161.
13. CHILTON, R. H.: *"MMIC TR Modules and Applications."* Microwave J., Sept. 1987.
14. CLARIDGE, P. A.: *"Design of Phased Array Antenna using Solid State T-R Modules."* Proc. 19th European Microwave Conf., 1989.
15. DAS, N. K., and POZAR, M.: *"Multiport Scattering Analysis of General Multilayered Printed Circuit Antennas."* IEEE Trans., 1992, PP. 469-481.

16. EAVES, J. and REEDY, E.: *"Principles of Modern Radars."* Van Nostrand Reinhold, New York, 1987.
17. EDWARDS, W. J., REES, D. S., and KAMMERLY, R.T.: *"Advanced Microwave Technologies."* IEEE EASCON Record, 1982.
18. ELLIOTT, R. S.: *"Antenna Theory and Design."* Prentice Hall India, 1981, Chap. 8.
19. ELLIOTT, R. S.: *"Basic Considerations in the Design of Arrays."* Proc. 15th Europe Microwave Conf., 1985, pp. 561-565.
20. GALANTI, G.: *"Advanced Radar Techniques and Systems."* IEE Radar, Sonar, Navigation, and Avionics Series 4., London, UK, 1993.
21. HARTWELL, T. E.: *"RASSR Array Evaluation."* IEEE NAECON-77 Record, 1977.
22. HERCZFELD, P. R., and ROSEN, A.: *"Optical Phase and Gain Control of a GaAs Transmit-Receive Module."* Proc. 18th Europe Microwave Conf., 1988.
23. IGI, S.: *"High Power and High Efficiency GaAs FETs in C-Band."* IEEE MTT-S Digest, 1988.
24. JEMISON, W. D., BERCELI, T., and JACOMB-HOOD, A. W.: *"Optical Control of Phase Shifter."* IEEE MTT-S Digest, 1990, pp. 233-236.
25. KIM, B., CAMILLERI, N., and WURTELA, M.: *"GaAs Power MESFETs and Monolithic Amplifiers."* IEEE Trans, 1989, pp. 1327-1332.
26. KIM, B.: *"GaAs Power MESFET With 41 Percent Power Added Efficiency at 35 GHz."* IEEE Electron Devices Letters, 1988, EDL-9, pp. 57-58.
27. KITCHENER, D., and PERINI, C. G.: *"Mutual Coupling in Infinite Arrays of Rectangular Apertures."* Proc. International Conference on Antennas and Propagation", 1989.
28. KNITTEL, G. H.: *"Radar Technology."* Artech House, Norwood, USA, 1979, Chap. 10.
29. KNORR, J.: *"Microwave Circuits and Devices, Handouts of the EC 3610 Course."* Naval Postgraduate School, Monterey, USA, 1995.
30. KOPP, W.S., and PRITCHETT, S. D.: *"High Efficiency Power Amplification for Microwave and Millimeter Frequencies."* IEEE MTT-S Digest, 1989.

31. LADBROOKE, P.: *"Statistical Design for Yield of MMICs."* Proc. Military Microwaves, MM-88, 1988, pp. 386-390.
32. LIVNE, A.: *"System Design Considerations in Fiber-Optic Networks for Active Array Antennas."* Proc. 19th Europe, Microwave Conf., 1989.
33. LOCKERD, R. M., and CRAIN, G. E.: *"Airborne Active Element Array Radars come of Age."* Microwave J., Jan. 1990.
34. MAGARSHAK, J.: *"European MMIC Activities."* IEEE MTT-S Digest, 1988, pp. 645-648.
35. MAILLOUX, R. J.: *"Phased Array Theory and Technology."* Proc. IEEE, 1982, pp. 249-291.
36. MCQUIDDY, D.N., GASSNER, R.L., HULL, P., MASON, J.S., and BEDINGER, J.M.: *"Transmit/Receive Module Technology for X-Band Active Array Radar."* Proc. IEEE, 1991, 79, pp. 308-341.
37. MORCHIN, W. C.: *"Airborne Early Warning Radar."* Artech House, Boston, USA, 1990.
38. NASTER, R J., and LANG, M.R.: *"Affordable MMIC Design for Phased Arrays."* Microwave J., March 1987, pp. 145-150.
39. NORRIS, G. B., and BARRAT, C.A.: *"GaAs MMIC Yield Modeling."* Proc. IEEE GaAs IC Symposium., 1990, pp. 317-320.
40. PAVIO, A.M., PAVIO, J.S., and CHAPMAN Jr., J.E.: *"The High Volume Production of Advanced Radar Modules."* Microwave J., Jan. 1989, pp. 139-148.
41. PENGELLY, R. S.: *"Monolithic Microwave Integrated Circuits."* Parts I and II IEEE MTT-S News Letter, Winter & Spring 1989.
42. PITZALIS, O.: *"Microwave to mm Wave CAE: Concept to Production."* Microwave J., State of the Art Reference Supplement, Sept 1989, pp. 15-49.
43. POZAR, D., and SCHAUBERT, DH.: *"Scan-Blindness in Infinite Phased Array of Printed Dipoles."* IEEE Trans., AP-32, 1984.
44. PRIOLO, M. and MEHARRY, D.: *"Transmit Receive Modules for 6 to 16 GHz Multifunction Arrays."* IEEE MTT-S Digest, 1990, pp. 1227-1230.

45. RUDGE, A. W. MILNE, K., OLVER, A. D., and KNIGHT, P.: *"Handbook of Antenna Design."* Peter Peregrinus, London 1986, Chap. 10.
46. SABATINI, S., and TARANTINO, M.: *"Multifunction Array Radar; System Design and Analysis."* Artech House, Boston, USA, 1994.
47. SCHLEHER, C.: *"Automatic Detection and Radar Data Processing."* Artech House, Boston, USA, 1980.
48. SCHLEHER, C.: *"Introduction to Electronic Warfare."* Artech House, Boston, USA, 1994.
49. SEEDS, A. J., and FLYNN, S. J.: *"New Developments in Optical Control Techniques For Active Phased Array Radars."* IEEE MTT-S Digest, 1988, pp. 905-908.
50. SHENOY, R. P.: *"Active Aperture Phased Arrays."* Alta Frequenza, 1989, LVIII, pp. 137-149.
51. SHENOY, R. P.: *"Recent Advances in Radar Technology."* Indian J. Radio e Space Physics, 1990.
52. SLIVA, R. J.: *"Analysis Shows Effects on T/R Modules."* Microwave and RF, 1988, pp. 79-86.
53. SPARKS, R. A.: *"Recent Microwave Applications to Radar in the US."* Proc. 19th Europe Microwave Conference, 1989.
54. TSAI, W.C. , GRAY, R., and GRAZIANO, A.: *"The Design and Performance of Supercomponents: High Density RF Modules."* Microwave J., Nov. 1983.
55. VORHAUS, J. L.: *"High Volume Manufacturing of a High Efficiency X-Band Power Module for Phased Array Applications."* IEEE MTT-S Digest, 1989, pp. 966-971.
56. WALSH, T.: *"Military Radar Systems."* Microwave Journal. Nov. 1988.
57. YAMADA, Y.: *"X- and Ku-Band High Power GaAs FETs."* IEEE MTT-S Digest, 1988, pp. 847-850.
58. YAW, D.: *"Electronic Warfare Antenna Systems -Past and Present."* Microwave Journal, Sep. 1981.

59. ZAGHLOUL, A. M., POTUKUCHI, J. R., and KROLL, R.T.: *"Analysis And Measurement of Tolerances in MMIC Active Phased Arrays."* Proc. 19th Europe Microwave Conf., 1988, pp. 966-971.

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